Development of Evaporation and Evapotranspiration Coefficients

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Abstract

In the 1980s, the U.S. Geologic Service, in cooperation with the U.S. Bureau of Reclamation, developed a water balance approach for estimating water consumption along the Lower Colorado River. Major estimated water consumption components were evaporation (E) and evapotranspiration (ET). These values were combined with a water balance applied to each of the four reaches of the river defined by the major dams, between Hoover Dam and the border with Mexico. The method is called the Lower Colorado River Accounting System (LCRAS). In 1990, Reclamation assumed responsibility for continued development of LCRAS and developed a strategy for improving the system. The strategy involved improving the accuracy of flow measurement, use of higher resolution remotely sensed digital satellite data, and improving the accuracy of E and ET estimates.

In 1998, monthly evaporation coefficients were developed for use with reference ET from AZMET and CIMIS micro-meteorological weather stations. Surface water temperatures were related to water temperatures measured below the dams creating the reservoirs. The Penman-Monteith (P-M) equation was used to estimate open water evaporation taking into account the advection of heat energy in the water inflows and outflows for each reach. The temperature of water leaving Hoover Dam is nearly constant year round ranging from 10 to 13 C. Average water temperatures increase in each of the four reaches until approaching mean air temperatures in the last of the four reaches below Imperial Dam.

Daily crop coefficients were developed for 16 classes of crops grown on lands irrigated along the Colorado River. Due to differences in planting and harvest dates two sets of coefficients were developed. One set was for the southern area near Yuma and one set was for areas further north.

The P-M equation was also used to estimate ET for each of the 13 categories of phreatophytes growing near the river. Albedo and bulk canopy resistance were varied during the year so that the resulting ET estimates were similar to lysimeter-measured ET for salt cedar. Very little data on leaf and canopy resistance existed for vegetation other than salt cedar. A set of daily phreatophyte coefficients was then developed based on the ratios of estimated phreatophyte ET to ET_o for each phreatophyte category.

Key Words:
Evaporation Coefficients, Evapotranspiration Coefficients, Penman-Monteith, Reference ET.

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Introduction

The companion paper by Paul Matuska and Jeff Milliken describes the history of the Lower Colorado River Accounting System (LCRAS) developed cooperatively by U.S. Geologic Survey (USGS) and the Bureau of Reclamation (Reclamation). Accounting for the distribution and consumption of water from the Lower Colorado River is required by the U.S. Supreme Court Decree of 1964 (U.S. Supreme Court, 1964). The Court defined consumptive use as *diversions from the stream less such return flows thereto as is available for consumptive use in the United States or in satisfaction of the Mexican treaty obligation*. Various methods had been evaluated for accounting for unmeasured return flow from irrigated lands along the Colorado River, but none were fully satisfactory in crediting diverters for unmeasured return flow.

In the 1980s, the USGS, in a cooperative project with Reclamation, developed a water balance computer program for estimating the consumptive use (CU) of water. The program was based on estimated evaporation (E) and evapotranspiration (ET) from crops and phreatophytes (Owens-Joyce and Raymond, 1996). It included adjustments based on the water balance for each of the four reaches of the river below Hoover Dam. In 1990, Reclamation assumed responsibility for continuing development of LCRAS and developed a strategy for improving the system. This strategy involved improved accuracy of flow measurement, use of higher resolution remotely sensed digital satellite data, and improved accuracy of E and ET estimates (Neff, 1992). ET estimates were based on vegetative types (crops and natural vegetation, or phreatophytes), and areas of each were determined from digital-image analysis of satellite data. ET estimates originally were based on a modified Blaney-Criddle formula (von Allworden et al. 1991). In the original program, the water balance residual was to be distributed only to crop ET estimates. In 1994, a preliminary review by the senior author indicated that the accuracy of the assigned water consumption to individual users could be improved by incorporating more recent technology for estimating ET and by distributing the residual to all measured and estimated components.

The senior author worked with Reclamation to develop methodology that would improve the accuracy of open water evaporation, and crop and phreatophye ET. The primary objective of the study was to provide evaporation and crop and other vegetation coefficients for use with daily grass reference ET (ET_o) values that were available from automated weather stations on the Arizona side (AZMET) and the California side (CIMIS) of the river. Three main sets of coefficients were developed (Jensen, 1998) which are being used with ET_o to provide estimates of the three major components of water consumption along the River. The purpose of this paper is to briefly describe the development of the three sets of coeffcients. Details are available in the full report (Jensen, 1998).

Background

A detailed description of activities leading to the development of LCRAS is provided in the companion paper by Matuska and Milliken. The residual, or closure term, in the original LCRAS model was vegetative consumptive use, CU_v. The greatest uncertainty in this component of LCRAS model was

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believed to be associated with the estimated phreatophyte ET. Phreatophyte ET made up about 1/3 of the total vegetation ET. The objectives of the work summarized in this paper were to develop evaporation and vegetation coefficients for use with daily ET_o to estimate E and ET_c and ET_v.

Procedures

In the original LCRAS program, ET rates were estimated using a modified Blaney-Criddle formula (von Allworden et al., 1991). During the past decade, significant improvements have been made in automated weather stations (AWSs), and networks have been developed to provide daily ET_o and other climate data measured with AWSs. Networks along the Lower Colorado River are operated by the Arizona Cooperative Extension (Arizona Meteorological Network, AZMET) and the California Department of Water Resources (California Irrigation Management Information System, CIMIS).

Climate data. Developing evaporation coefficients required estimating net radiation for water surfaces. Net radiation estimates were also needed to develop phreatophyte coefficients. Detailed daily climate data for a three-year period, 1995-97, were obtained from AZMET and CIMIS networks for use in estimating net radiation and evaporation.

Energy balance. The available energy is generally the main factor that limits open water evaporation. The concept of estimating evaporation using energy balance was developed in the 1920s. Bowen (1926) showed that water vapor and sensible heat were transferred by the same aerodynamic mechanism, and others later showed that the direction of transfer was determined by the gradients of water vapor and temperature. The ratio of the vapor gradient to the temperature gradient is known as the Bowen Ratio (BR). Cummings and Richardson (1927) showed that Bowen's conclusions regarding the BR were consistent with observations. McEwen (1930) and Cummings (1946) showed that lake evaporation could be estimated accurately using energy balance theory and applying the Bowen Ratio Energy Balance methodology. The energy balance method has become a reliable method for estimating the rate of evaporation, especially if measurements can be made over water surfaces. The energy balance becomes more complicated where there are inflows and outflows of water because of the advection of heat energy in water.

The primary source of energy for evaporation is net radiation, R_n, which consists of incoming solar radiation, R_s, minus reflected solar radiation, αR_s, and net long-wave radiation, R_{nL}. Reflected daily solar radiation is the fraction of incoming direct and diffuse solar radiation that is reflected from the ground or water surface. It is estimated as αR_s where α is the mean daily albedo for the surface. All surfaces emit long-wave radiation in proportion to the 4th power of the absolute temperature of the surface. Similarly, atmospheric gases emit long-wave radiation. The net long-wave radiation is the difference between downward long-wave radiation, R_{dL}, and upward long-wave radiation, R_{uL}.

Other energy sources. Other sources of energy consumed in evaporation are sensible heat transferred from warm air to a cooler water surface and advection of heat energy into or out of water bodies. The rate

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of transfer of sensible heat is dependent on wind speed and air temperature gradients over water surfaces. Advection of heat energy in water depends on flow rates and temperature of water entering and leaving the water body. In this case, the primary inflows to reaches were the flows released from Lake Mead and from each of the other dams, and the outflows were the exports of water to California via the Colorado River aqueduct and to Arizona via the Central Arizona Project Canal, and net diversions of water from the river. Other water inflows and outflows include precipitation and runoff from adjacent lands and evaporated water. The largest diversion from the river is to the Imperial Irrigation District and the Coachella Valley Water District via the All American Canal.

Surface water temperature. Surface water temperatures in the river and the two reservoirs, Lake Mohave and Lake Havasu, were needed to estimate net radiation. Thermal stratification, mainly in the upper 2 to 5 meters, normally occurs in lakes and reservoirs due to incident solar radiation. Water temperature profiles have been measured in both Lake Havasu and Lake Mohave (Roline and Lieberman, 1985; and Paulson and Baker, 1984). Thermal stratification begins in April and May and the reservoirs are fully stratified by June. The water was typically fully mixed by October or November due to the high flows. The similarity of surface water temperatures in the two reservoirs further indicates that solar radiation and air temperature rather than inflow and outflow rates and temperatures control reservoir surface water temperatures. Estimates of surface water temperatures were based on adjustments of current temperatures below Davis and Parker Dams to approximate 1984 surface temperatures. These data, although limited to several sites, enabled estimating the average daily rate of change in heat energy stored or released from water in these reservoirs and surface water temperatures.

Net radiation. Net radiation, the major component of the energy balance, was based on a recently calibrated equation for downward long-wave radiation and on average surface water temperatures for upward long-wave radiation.

$$R_n = (1 - \alpha_w) R_s\!\downarrow + R_{Ld}\!\downarrow - R_{Lu}\!\uparrow \qquad (1)$$

where R_n is net radiation, MJ/(m^2 day), α_w = water surface albedo, ε_{ac} is atmospheric emittance for clear skies (Brutsaert, 1982), R_{Ld} = downward long-wave radiation, and R_{Lu} = upward long-wave radiation from water surfaces, MJ/(m^2 day).

Albedo. The USDA Soil Conservation Service (SCS, 1993) developed equations for estimating seasonal variation in the mean daily albedo for grass using the hourly relationships presented by Dong et al. (1992). Harbeck et al. (1958) measured incoming and reflected solar radiation data for Lake Mead and used relationships developed during the earlier Lake Hefner studies to estimate hourly reflected solar radiation based on the sun altitude and cloud cover. An evaluation of albedo values reported by Harbeck et al. (1958) indicated that the seasonal change in albedo for grass paralleled the seasonal change in albedo for water, and that the same equation could be adapted to water surfaces by changing only the constant.

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Downward atmospheric long-wave radiation. Brutsaert (1982), (Eq . 6.18) presented an equation for atmospheric emissivity, $\varepsilon_{ac} = 1.24(e_a/T_a)^{1/7}$ where e_a is air vapor pressure in mb, or vapor pressure at dew point, and T_a is temperature in K. For vapor pressure in kPa, either the constant must be changed or vapor pressure in kPa must be multiplied by 10. Culf and Gash (1993) calibrated Brutsaert's original equation for dry climate replacing the constant 1.24 with 1.31, i.e., $\varepsilon_{ac} = 1.31(10\, e_a/T_{kavg})^{1/7}$ for e_a in kPa. The USGS estimated the reflectance of long-wave radiation, r, from water surfaces to be 0.03 based on measurement made during the 1961-1962 Salton Sea study (Hely et al., 1966). The combined downward long-wave radiation equation including the Culf and Gash (1993) calibration of Brutsaert's original equation is:

$$R_{Ld} = (1 - r)1.31 \frac{4.90(T_{kmax}^4 + T_{kmin}^4)/2}{10^9} \left(\frac{10 e_a}{T_{kavg}} \right)^{1/7} \tag{2}$$

where e_a is saturation vapor pressure at dew point temperature, kPa, r = the reflected long-wave radiation from water, T_{kmax} and T_{kmin} are the average absolute maximum and minimum air temperatures (K), and the Stefan-Boltzmann constant is $\sigma = 4.903/10^9$ MJ/(m^2 day).

Upward long-wave radiation for a cloudless day was calculated using the emissivity for water surface, $\varepsilon_w = 0.97$ and the estimated surface water temperature.

$$R_{Lu} = \epsilon_w \frac{4.903}{10^9} (T_{kw}^4) \tag{3}$$

where T_{kw} is the absolute surface water temperature. For this study, 1993-1995 water temperature data from the Geologic Survey (USGS, 1995) and data provided by Reclamation were used. Mean monthly surface water temperatures for Lake Mohave and Lake Havasu along with water temperatures below Hoover Dam, Davis Dam and Parker Dam were based on relationships developed between surface temperatures and water temperatures below Davis Dam for Lake Mohave and below Parker Dam for Lake Havasu.

Net long-wave radiation. Net long-wave radiation was calculated as the difference between the cloudless day downward and upward long-wave radiation modified by the ratio of actual to potential cloudless day solar radiation.

$$R_b = \left(a \frac{R_s}{R_{so}} + b \right) (R_{Ld} - R_{Lu}) \tag{4}$$

where $(R_{Ld} - R_{Lu}) = R_{bo}$ is net long-wave radiation on a clear day, MJ/(m^2 day), R_s = measured solar radiation, and R_{so} = clear-day solar radiation. Adjustments for cloud cover based on R_s/R_{so} used the same coefficients as were used for reference ET, i.e, a = 1.126 and b = -0.07 (Wright, ASCE Manual 70, p. 137).

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Clear-day solar radiation. Clear-day solar radiation was based on equations developed by Allen (1996) and standard equations for calculating extraterrestrial solar radiation (Knapp et al., 1990).

Penman-Monteith Equation.

The Penman-Monteith (P-M) equation was used to estimate evaporation and phreatophyte ET to develop evaporation and phreatophyte coefficients. The P-M combination equation expressed in the same format as for the Penman equation is:

$$\lambda E = \frac{\Delta}{\Delta + \gamma*}(R_n - G) + \frac{\lambda}{\Delta + \gamma*}\rho\frac{0.622\lambda}{P}86{,}400\frac{(e_o - e_a)}{r_a} \tag{5}$$

where ϱ = the density of moist air, kg/m^3, P = atmospheric pressure, kPa, $\gamma* = \gamma(1 + r_s/r_a)$, r_s = surface resistance, and r_a = aerodynamic resistance in s/m. Since the surface resistance is "zero" for water, i.e. $\gamma = \gamma*$, the radiation component of the combination equation is identical to that in the Penman equation (Penman, 1963). The aerodynamic resistance is based on the heights of air temperature, humidity and wind speed measurements and surface roughness as reported by Allen et al. (1989).

Wieringa (1992) recently updated roughness length values and reported a value of z_{om} = 0.0002 m (2×10^{-4} m) for the sea with a free fetch of several km, but indicated that it was dependent on wind speed. Furthermore, he indicated that where changes in surface roughness occur, we need to consider surface conditions for several km upwind. Since our first interest was to estimate evaporation from reservoirs, initial calculations were made using z_{om} = 0.0002 m. Since wind speed data over water surfaces in the reservoirs were not available, wind speeds were assumed to be the same as those measured at the weather station sites. Wind speeds at the AZMET and CIMIS weather station sites along the Lower Colorado River are generally very low. Likewise, no atmospheric water vapor pressure data were available from comparable heights above water surfaces and vapor pressures were also assumed to be the same as those measured over irrigated land at the weather stations.

The automated weather stations operated by CIMIS report mean daily vapor pressure. The automated agricultural stations operated by AZMET report mean daily vapor pressure deficit. Since AZMET does not report humidity at maximum and minimum temperatures, the mean daily vapor pressure was based on the saturation pressure at average temperature and mean relative humidity which is reported.

Advected energy. The most difficulty encountered in using the combination equation was in estimating the rate of energy advected in flowing water. The rates of change in heat energy stored in Lake Mohave and in Lake Havasu were based on temperature profile data and the change in monthly water storage in these reservoirs. These rates were relatively small compared to the advected inflow and outflow energy and export of water for these two reaches. Since water temperatures increased in each reach from Hoover Dam to Morelos Dam and large flow rates are involved, mean daily heat energy absorbed by water from solar radiation, G_w, is not available for evaporation.

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The mean monthly value of G_w for each reach was estimated by first converting all flow data and volume changes in storage to cubic meters per day. Then, the heat energy in the water based on 0-°C was calculated by multiplying flow data by their respective temperatures using a heat capacity of 4.1868 MJ/m^3. The average value of G_w in $MJ/(m^2 \text{ day})$ was then calculated for each reach based on outflow energy, change in storage energy, and exported energy less inflow energy per unit area of water surface. For the reaches Davis Dam to Parker Dam and Parker Dam to Imperial Dam, energy in other major net inflows and outflows of water such as tributary and ground water inflows and ET by phreatophytes also had to be considered. For the reach Imperial Dam to Morelos Dam, there was insufficient data to use this approach because of the complex flows and lack of temperature data. For this reach, the difference between flow above Imperial Dam minus the flow to the All American Canal below Pilot Knob and the flow above Morelos Dam and the difference in water temperatures from above Imperial Dam to above Morelos Dam were used to estimate the magnitude of G_w.

Evaporation coefficients. Evaporation coefficients for use with ET_o from AZMET and CIMIS stations were calculated daily based on evaporation estimates using AZMET and CIMIS climate data for the three-year period, estimated surface water temperatures and estimated advected heat energy for each reach. The evaporation coefficient for each day was calculated as $K_w = E/ET_o$. Calculated daily values of K_w are more variable than daily crop coefficients because of the buffering effect of water compared to cropped lands. Mean monthly evaporation coefficients for each reach for use with ET_o were based on moving 9-day means of K_w for the three years of daily values. The resulting mean annual evaporation coefficients ranged from 0.77 for the Hoover Dam to Davis Dam reach to 0.86 for the Imperial Dam to Morelos Dam reach.

Generalized Crop Curves

Daily crop coefficients were developed for the 16 crop classes listed in Table 1 in the paper by Matuska and Milliken. The general shape of the crop coefficient curve for each crop is based on the linear form used by FAO in its publication on crop water requirements (Doorenbos and Pruitt, 1977) as updated (Allen et al., 1998). Seasonal crop ET estimates using the updated FAO coefficients and the three-year data set were evaluated by comparing them with estimates developed for use in the Imperial Irrigation District (IID) (Allen, 1998), and with measured values of ET reported by Erie et al. (1982). Coefficients for alfalfa grown for seed were based on coefficients previously developed for the IID. Coefficients for alfalfa grown for hay represent the potential maximum ET that can be expected under pristine crop conditions if cut hay is removed immediately and soil water is maintained so as not to limit ET at any time. These values are estimated to be about 15 percent too high for normal farm practices because hay is not always removed immediately after cuttings, non-uniformity of field stands, and some water stress between irrigations (Hill et al., 1983). Coefficients for maximum potential alfalfa ET were multiplied by 0.85 to represent field conditions. For citrus, coefficients developed for the IID which were based on data from California, were used instead of the FAO values.

The magnitude of the coefficient for the initial growth stage from planting to about 10 percent cover is dependent on the frequency of irrigation (or precipitation) or the irrigation interval, I_w, in days, and

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the evaporative demand during the initial period, ET_{oi}. Allen et al. (1998) converted a table by Doorenbos and Pruitt (1977) to equation form which was used to adjust for irrigation frequency and reference ET. The magnitudes of K_{c2} and K_{c3} were also adjusted for more or less arid climates and wind speeds with equations by Allen et al. (1998) based on wind speed, minimum relative humidity, and crop height. Since minimum relative humidity is not reported uniformly from AZMET and CIMIS stations, minimum relative humidity was estimated by substituting minimum temperature for dew point temperature as suggested by Allen et al. (1996).

Other Adjustments. Adjustments to the length of the growth stages were made based on information provided by agricultural specialists along the Lower Colorado River, by comparison with crop coefficients developed for the Imperial Irrigation District by Allen (1998), and with crop ET data and crop ET curves reported by Erie et al. (1982). In order to reduce the number of sets of crop coefficients and still maintain the general FAO-type crop curve, the frequency of irrigation during the planting to 10 percent cover stage was adjusted by assuming the initial irrigation interval included either a preplant or an irrigation for germination and plant establishment.

Other Vegetation Coefficients

Daily vegetation coefficients were developed for the 13 phreatophyte classes listed in Table 2 of the paper by Matuska and Milliken. The general shape of the vegetation coefficient curve for phreatophyte group was also based on the linear equation form used by FAO. The most common species of phreatophyte of concern is saltcedar (*Tamarix chinensis* Lour., or *Tamarix ramosissima*). Observations of saltcedar on the flood plains of the Colorado and Gila Rivers indicated that saltcedar is not always well-supplied with water, but is under some water and salinity stress. Many early values of annual ET, up to 2,200 mm (86 in.) were obtained in tanks or lysimeters. Measured stomatal resistances show large changes during the day, typically increasing in the afternoon. Gay et al. (1976) calculated average canopy resistance of 190 s/m for four days from 0830 to 1830. Weeks et al. (1987) reported that saltcedar foliage temperatures were always higher than air temperatures. In mid-June, mid-afternoon foliage temperatures on old growth saltcedar were 43-45 °C while mowed saltcedar fronds had temperatures of only 36-38 °C. Gay and Sammis (1977) calculated a canopy resistance of 390 s/m for one day, which seems to be high. Gay (1986) reported greenup for saltcedar begins on 23 March and dormancy occurs on 11 November along the Lower Colorado River.

Culler et al. (1982) reported an average annual ET of 1,090 mm (42.9 in.) for a reach of the Gila River ranging from 1,420 (56 inches) for dense stands to 630 mm (25 in.) for no phreatophytes where the water table was at a depth of 2.4 m (8 ft). Weeks et al. (1987) made a thorough study of saltcedar ET citing an earlier study showing that ET is not linearly related to volume density. This is supported by data by van Hylckama (1974) who found that thinning saltcedar to 50 percent density decreased ET only 10-15 percent. Weeks et al. (1987) reported only 770 mm (30 in.) of ET for old growth, which reflects the effects of high frond temperatures, and 1,070 mm (42 in.) for the mowed site. In the study by van Hylckama (1974), the 1961-63 data seem to be the most reliable. He measured 1,490 mm (59 in.) in lysimeters with the water table at a depth of 2.1 m (6.9 ft), and about

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1,000 mm (39 in.) with the water table at 2.7 m (8.9 ft). Salinity increased greatly in the lysimeters with higher water table levels. van Hylckama (1974) measured wind speed at a height of 4 m over saltcedar that was 2.5-3.0 m in height. These data support the estimates of wind speed at 2 m over phreatophytes as described later.

Daily rates of saltcedar ET vary widely. Gay and Fritchen (1979), using Bowen Ratio equipment, measured 9 mm/day (0.35 in./day) from 4.5-m saltcedar at the Bernardo, NM site with the depth to the water table of 1.5 m. Gay et al. (1976) reported an average ET rate of 6.7 mm/day (0.26 in./day) over a four-day period in June at this site. Weeks et al. (1987) cite a 1981 Reclamation study near the Gila River over 48 days where 5.8 mm/day (0.23 in./day) was measured from 17 August to 3 October and 7 mm/day was measured over rapidly growing saltcedar. The vegetation coefficients for class Sc-low and class Sc-high and Yuma ET_o data for September gives an ET_v estimates of 5.9 mm/day and 6.6 mm/day, respectively.

The P-M estimates were based on canopy resistance of 200 s/m and 175 s/m after greenup for classes 5 and 6, respectively, and 500 s/m for dormant periods. A two-week period was used for greenup to full leaf and a two-week from full leaf to dormancy. Minimum albedo was 0.18 for class Sc-low and 0.16 for class Sc-high adjusted by calendar day using the SCS albedo equation. Generally, the P-M estimates tended to lag the measured values.

Wind Speed Adjustment. Wind speeds measured 2 m above 10-20 m trees have been found to be only about 0.5 of that measured over nearby short grass (Allen et al., 1996). Allen and Wright (1996) developed an equation for translating wind speed measurements from the AWS site to other areas. Estimates of wind speeds 2 m above 3-5 m tall phreatophyte vegetation ranged from 0.81 to 0.85 of that measured at 2 m above grass.

Zero-Plane Displacement and Roughness Length. Standard equations were used to estimate zero-plane displacement and roughness lengths (Allen et al., 1996).

Albedo. Ranges in mean daily albedos for natural surfaces were given Monteith and Unsworth (1990). They reported that maximum albedo values are recorded over relatively smooth surfaces such as closely cut lawns, and for crops of 0.5 to 1 m in height, albedo is usually between 0.18 and 0.25 when ground cover is complete. These data were used to select a low value (representing CD 173 when the mean solar altitude is the greatest) for each phreatophyte group.

Other Adjustments. The magnitude of the vegetative coefficient for the initial growth stage until greenup was estimated similar to the initial stage of crop. The lengths of the growth stages were adjusted so that the linear vegetative curves approximated reported changes due to greenup and dormancy. Ratios of measured ET by van Hylckama (1974) and Gay (1986) to ET_o were also used as a guide in setting these lengths.

Evaporation From Soil. Weeks et al. (1987, Fig.2) presented data showing annual evaporation as reported for various soils vs. depth to the water table. Selected data scaled from this figure with data

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from van Hylckama as measured over several years showed the strong influence of depth to the water table and soil texture on evaporation from the soil surface. Depth to the water table is an extremely important variable affecting evaporation from bare soil.

Coefficient for Marsh and Barren Classes. Estimated coefficients for the Marsh class using the linear format were based on coefficients presented by Allen et al. (1996). Coefficients for bare soil evaporation were based on evaporation data from lysimeters with a 1.2-m depth water table by van Hylckama (1994).

Phreatophyte Coefficients. Development of vegetation coefficients for phreatophyte types began with the Penman-Monteith equation. Limited data on soil heat flux, G, under saltcedar as measured by Weeks et al. (1987) were used to develop the an empirical equation for daily soil heat flux. The resulting vegetation coefficient represents the ratio of estimated ET for a phreatophyte group, ET_v, to the reference ET reported by AZMET and CIMIS, ET_o.

Results

Evaporation. Estimated annual evaporation rates based on the three-year data set range from 1550 mm per year (5.1 ft) for the Hoover Dam to Davis Dam reach to 1780 mm per year (5.8 ft) for the Imperial Dam to Morelos Dam reach. Estimates using the coefficients and average 1993-1997 ET_o values range from 1680 to 1830 mm. Estimated annual evaporation for the Salton Sea, after adjusting for salinity, is 1850 mm per year (5.8 ft) (Hely et al., 1966).

Crop ET. Estimated crop ET values using the linear crop curves and the three-year ET_o data set generally agreed with measured ET or estimates made for the Imperial Irrigation District.

Phreatophyte ET. The main sources of measured ET are 1961-63 data from van Hylckama's lysimeters, and estimated seasonal and annual rates by Gay (1986) and Gay and Hartman (1982). One example of ET reported by van Hylckama (1974) for water table depths of 2.1 m (6.9 ft) and 2.7 m (8.9 ft), and P-M ET estimates for class Sc-low along with 1995 average Yuma ET_o indicates that estimates agreed reasonably well from November through June, but deviate for July-September. Annual total estimated ET for class Sc-low agrees closely with average van Hylckama's 2.1-m values.

Coefficients. Daily coefficients for crop and vegetation classes were provided to Reclamation in tables and electronic form. They have been incorporated into the LCRAS methodology and have been used to estimate ET for the 1995 - 1998 reports. From 1995 the closure or residual of the water balance has generally decreased. In 1998 the closure was within 2% (percent of the inflow to the reach) for each reach and three of the reaches had closure within 1%. The total residual for the River between Hoover Dam and Mexico was 12.8×10^6 m^3 (10,380 AF).

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